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Reply by Authors

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We welcome the response from Baldev Raj to our article.[1] However, it does not satisfactorily address the issues raised therein.

To begin with, it does not explain how 100 MJ is an upper bound on mechanical energy that could be released in a core disruptive accident (CDA). Raj states that safety studies have shown that mechanical energy release from loss of coolant flow together with failure of safety systems is less than 1 MJ. This contradicts DAE's published studies of the PFBR,[2] cited in our article, which show that energies on the order of 1000 MJ are possible. A key assumption in this calculation is the reactivity "insertion" rate (which depends on how much of the core collapses, in what configuration and how fast); the 100 MJ limit is based on assuming that only a part of the core participates in the accident. As we show in our article, the DAE's analysis that calculates the effect of the initiating events on the extent of core melting is limited by omissions (ignoring of cladding failure modes and the effects of burnup on fast reactivity feedbacks as well as fuel thermophysical properties) and therefore is unduly optimistic.

Regarding the small CDA mechanical energy to thermal power ratio estimated for the Prototype Fast Breeder Reactor (PFBR) as compared to previous fast reactors, Raj points to other recent designs with even smaller figures. The problem is that the reactors he offers as counter-examples have not yet been cleared for construction by the appropriate safety regulators in those countries, let alone constructed. We see no reason to expect that French regulators, for example, would be satisfied with a reactor design that offers less containment strength than the Superphénix, after the series of accidents that the Superphénix experienced. The only reactor under construction in the list Raj offers is the Russian BN-800. However, this reactor has been designed to have a very small or negative sodium void coefficient and therefore is not the most relevant benchmark for the PFBR which has a large positive value.[3] The BN-800's containment design must also be seen in the background of the safety performance of Russia's breeder program. The largest reactor constructed so far, the BN-600, experienced 27 sodium leaks between 1980 and 1997, 14 of which resulted in sodium fires.[4] In most, if not all, cases, it appears that the reactor was not even shut down and continued operating as the fires were raging, indicating that inadequate priority is given to safety.

Finally, the larger question is whether this ratio should fall below its value in the previous batch of fast reactors built or designed in the 1970s and 1980s, given that their accident studies already considered the effect of fast Doppler feedback.

Raj details various reasons in support of the argument that such an accident is very unlikely to occur. However, there is a body of literature that suggests that it is difficult if not impossible to anticipate all failure modes in advance because a nuclear reactor's components and systems interact in unanticipated ways ("Normal Accident theory").[5] Therefore, despite the best intentions of the designers and engineers at the DAE, there is still a residual chance of a CDA and it is important that we understand its possible magnitude in relation to what the containment can withstand.

A second argument by Raj is that fast acting Doppler and fuel axial expansion feedbacks, both of which are negative, will occur well ahead of sodium boiling and prevent the positive void effect from expressing itself. The Southwest Experimental Fast Oxide Reactor (SEFOR) experiments that he cites involved such a situation, where an induced power increase was compensated by negative feedback effects arising from within the fuel pins.[6] However, the situation is different during a loss of flow accident such as during the shutdown of coolant pumps; here, the coolant heats up and boiling can occur before the fuel pin temperatures rise significantly enough to induce negative reactivity effects in the core. The DAE's own article on loss of flow accidents for the PFBR acknowledges that coolant boiling occurs even when the shutdown system is operative for a scenario when the flow halving time is 100 seconds, much higher than the PFBR's design.[7] In our article (Appendix 3) we discuss the evidence that the DAE's own analysis belies its claims that the reactor can be safely shut down in such an accident. Moreover, the failure of shutdown systems can only increase the likelihood and extent of coolant voiding and resulting positive feedback effects, and this situation appears to not have been analyzed by the DAE. In addition, the fast acting feedback due to fuel expansion that Raj mentions can become less effective as the fuel pins are progressively irradiated in the core, and cannot be taken for granted. We have discussed this in our article (Appendix 2).

Next, we address the issue of containment design. We agree that the DAE knows how to build stronger containments, and its designs for its pressurized heavy water reactors are evidence. Our concern is that with mechanical energy releases larger than 100 MJ, sodium expulsion into the containment would be correspondingly higher. Based on our assessment that a CDA can release several hundred MJ of mechanical energy, we extrapolate that as much as twice the design pressure can be generated in the containment from sodium burning.[8] This is based on assuming that the pressure vessel remains intact, and its top cover remains in place, as does the DAE in its safety studies of the containment. If either of these is affected, the pressures in the containment can be much higher. Therefore, we do not have to appeal to other design considerations to make the case for a much stronger containment for the PFBR.

Finally, an institutional concern that needs highlighting pertains to Raj's reference to the PFBR design being approved by a safety committee. The organization responsible for the regulation of nuclear safety in India is the Atomic Energy Regulatory Board (AERB). The AERB reports to the Atomic Energy Commission (AEC), which is chaired by the head of the Department of Atomic Energy (DAE). The Chairman of the Nuclear Power Corporation (NPC) is also a member of the AEC. Thus, both the DAE and the NPC exercise administrative powers over the AERB. Regulatory oversight is further weakened by the AERB's lack of technical staff and testing facilities. As a former chairman of the AERB has observed,

> 95 per cent of the members of the AERB's evaluation committees are scientists and engineers on the payrolls of the DAE. This dependency is deliberately exploited by the DAE management to influence, directly and indirectly, the AERB's safety evaluations and decisions. The interference has manifested itself in the AERB toning down the seriousness of safety concerns, agreeing to the postponement of essential repairs to suit the DAE's time schedules, and allowing continued operation of installations when public safety considerations would warrant their immediate shutdown and repair.[9]

The current Secretary of the AERB is Om Pal Singh, who conducted some of the safety analyses of the PFBR that we have critiqued. Under such circumstances, review is unlikely to be rigorous.

NOTES AND REFERENCES

1. Ashwin Kumar and M. V. Ramana, "Compromising Safety: Design Choices and Severe Accident Possibilities in India's Prototype Fast Breeder Reactor," *Science and Global Security* 16 (2008).

2. Om Pal Singh and R. Harish, "Energetics of Core Disruptive Accident for Different Fuels for a Medium Sized Fast Reactor," *Annals of Nuclear Energy* 29 (2002).

3. IAEA, "Fast Reactor Database: 2006 Update," (Vienna: International Atomic Energy Agency, 2006).

4. O.M. Saraev, "Operating Experience with Beloyarsk Power Reactor BN600 NPP," in *Technical committee meeting on unusual occurrences during LMFR operation* (Vienna, Austria: International Atomic Energy Agency, 1998).

5. The most important of these remains, Charles Perrow, *Normal Accidents: Living with High-Risk Technologies*, Rev. ed. (Princeton, NJ: Princeton University Press, 1999).

6. H.-H. Hennies et al., "The Fast-Neutron Breeder Fission Reactor: Safety Issues in Reactor Design and Operation [and Discussion]," *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences* 331, no. 1619 (1990).

7. It has been reported that the coolant pumps are designed to induce a flow halving time of 12 seconds. The DAE's analysis of loss of flow accident in the PFBR is discussed in S. R. Paranjpe, Om Pal Singh, and R. Harish, "Influence of a Positive Sodium Void Coefficient of Reactivity on the Consequences of Transient Overpower and Loss-of-Flow Accidents in a Medium-Sized Fast Reactor," *Annals of Nuclear Energy* 19, no. 7 (1992).

8. Kumar and Ramana, "Compromising Safety: Design Choices and Severe Accident Possibilities in India's Prototype Fast Breeder Reactor."

9. A. Gopalakrishnan, "Issues of Nuclear Safety," *Frontline*, March 13–26, 1999.